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Amblyopic deficits in detecting a dotted line in noise☆

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Abstract

We compared detectability of a dotted line masked by random-dot noise for the amblyopic versus non-amblyopic eye of two strabismic amblyopes. Small but consistent deficits in the amblyopic eye of these observers were found, and shown to be limited to dotted-line targets composed of greater than seven dots (with performance being normal for targets of less than seven dots). These deficits were unrelated to impaired visual acuity, impaired sensitivity to dot density, and differential positional uncertainty between the eyes of our observers. The deficits were also unlikely to be due to CSF losses due to abnormal low-spatial-frequency filters involved in detecting long chains of collinear dots. Instead, the results of simulations indicate that the inefficiency in utilising large numbers of dots is due to deficits of global, integrative processes in strabismic amblyopes. These simulations also show that while neither undersampling nor positional uncertainty of inputs into integrative processes can themselves account for the amblyopic deficits, if such abnormal inputs lead to the development of *stunted* integrative processes then impaired sensitivity to long chains of collinear dots is indeed predicted.

Keywords: Perceptual grouping; Amblyopia; Strabismic amblyopia

1. Introduction

Amblyopia is a developmental disorder of the visual system that leads to poor acuity in the amblyopic eye (Levi, 1988; Watt & Hess, 1987). In strabismic amblyopia this results from uncorrected deviations in fixation (squint). This type of amblyopia is characterised by losses in position acuity that are greater than expected on the basis of resolution acuity (Levi & Klein, 1985; Levi, 1991). It is possible that strabismic deficits reflect cortical spatial undersampling; that is, a sparse cortical receptive-field grain (Levi & Klein, 1985; Levi, Klein & Yap, 1987; Levi, 1990). Alternatively, strabismic deficits may reflect uncalibrated neural jitter; that is, 'scrambling' of the retinotopic map resulting in high intrinsic positional uncertainty (Hess, Field & Watt, 1990; Watt & Hess, 1987). Recent work has also led to the suggestion that more global tasks requiring integration across numerous cortical units might also be affected in strabismic amblyopia. For example, Kovács, Polat and Norcia (1996) and Kovács, Polat, Pennefather, Chandna and Norcia (2000) reported that amblyopes perform poorly in a task requiring perceptual grouping, and Polat, Sagi and Norcia (1997; see also Polat & Sagi, 1993) reported that long-range contour interactions were abnormal. It is uncertain, however, whether these results are a consequence of the reduced extent of global, integrative processes (Kovács et al., 1996, 2000), or whether they simply reflect deficits carried over from cortical units feeding into these global processes (Hess et al., 1997; Levi & Sharma, 1998). In support of the latter proposition, Hess et al. demonstrated that poor perceptual grouping performance in strabismics can be modelled by increased positional uncertainty (i.e. uncalibrated neural jitter) of cortical units, and Levi and Sharma showed that context-dependent integration operates normally in strabismic amblyopes when their contrast sensitivity deficits are taken into account.

The implication of the above to amblyopic deficits is complicated by the availability of two general solutions that may be implemented by the visual system to

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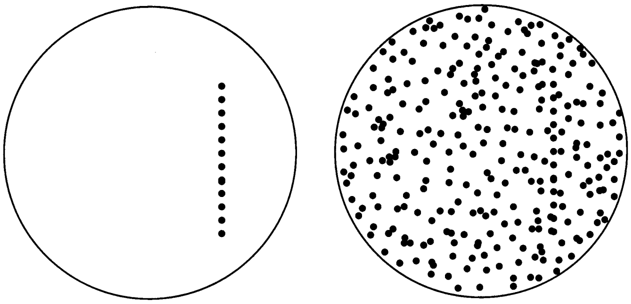

Fig. 1. Representation of the stimuli employed in the experiments. On the right, a target composed of 12 vertically-aligned and equally-spaced dots is embedded in a background of random-dot noise. For comparison, the same target is shown on the left in isolation.

accomplish the task of detecting global structures composed of collinear local elements. The first solution (we refer to models implementing this solution as '*spatial-frequency models*') does not require perceptual grouping per se, but instead involves detection of collinear elements by cortical units (perhaps simple or complex cells) having receptive fields large enough to allow simultaneous excitation from the elements making up the global structure (Beck, Sutter & Ivry, 1987; Bergen & Adelson, 1988; Caelli, 1985), with units tuned to high spatial-frequencies being most efficient at detecting clusters of small or closely-spaced elements, and units tuned to low spatial-frequencies being most efficient at detecting large clusters of elements or widely-spaced elements.

The second solution is to integrate (presumably in accordance with Gestalt principles) information provided by local units involved in detecting only the local elements of global structures. In one variant (we refer to models of this sort as '*association models*' after the association fields described by Field, Hayes & Hess, 1993) integration of local information is carried out via local cooperative interactions between cortical units with similar orientation selectivity and which are in close proximity (psychophysical evidence: Beck, Prazdny & Rosenfeld, 1983, Beck et al., 1987; Field et al., 1993; Grossberg & Mingolla, 1985; Nothdurft, 1992; Polat & Sagi, 1993, 1994; Smits, Vos & van Oeffelen, 1985; neurophysiological evidence: Fitzpatrick, 1996; Mitchison & Crick, 1982; Rockland & Lund, 1982; Schmidt, Goebel, Löwel & Singer, 1997; Sinsich & Blasdel, 1995). In a second variant (we refer to models of this sort as '*collator models*' after Moulden, 1994) integrative processes are not implemented via local interactions but are coded for explicitly by higher-order units that combine outputs from a fixed group of cortical subunits (Moulden, 1994; Morgan & Hotopf, 1989; Mussap & Levi, 1996, 1997).

To explore the nature of amblyopic deficits in perceptual grouping in the context of the above models, we compared detection of a line comprised of collinear dots embedded in random-dot noise (see Fig. 1; also French, 1954; Uttal, 1975; Moulden, 1994, for similar methods) for the amblyopic versus non-amblyopic eyes of two strabismic amblyopes, and attempted to relate performance differences to interocular differences in positional uncertainty, visual acuity, and sensitivity to dot density.

2. General methods

2.1. Observers

Observers were two strabismic amblyopes who were highly practised at making psychophysical judgements. Clinical details are given in Table 1.

2.2. Apparatus and stimuli

All stimuli were generated by a 486 PC interfaced with a Vision Works™ II graphics board. The computer used to generate the stimuli also controlled selection and presentation of the stimuli. Stimuli were displayed on a US Pixel™ high resolution monochrome monitor at 2.3 m distance from the observers. Stimuli were 84 cd m^{-2} and were presented in an aperture 6° in diameter, set at 56 cd m^{-2}. The area around the circular aperture was approximately 0 cd m^{-2}. Except for the 'scaling' control experiment used to test the effects of differential monocular visual acuity, all dot stimuli were 6.5 min in diameter.

Table 1
Visual characteristics of amblyopes

Observer	Age	Sex	Eye	R_x	Acuity[a]	Fixation[b]	Strabismus
R.H.	32	M	OD	$-1.00/-0.50\times170$	20/15	Central	Microtropia
			OS	$-1.50/-1.50\times10$	20/70	Unsteady	L. ET., 2Δ
A.J.	27	F	OD	$+5.50/-2.50\times20$	20/60	1.5°	Constant
			OS	-0.25	20/15	Temporal central	R. XT., 4Δ

[a] Seventy-five percent correct on Davidson-Eskridge charts (at the time of these experiments).
[b] Fixation determined with Haidinger's brushes and visuoscopy.

2.3. Procedures

Target detection thresholds were obtained using a self-paced method of constant stimuli with trial durations of 150 ms. Unless stated otherwise, in each block of 180 trials observers were presented with a series of equally spaced (with gap size equal to dot diameter; i.e. 6.5 min) and aligned target dots embedded in random dot noise. Their task was to indicate whether the target dots were aligned along the horizontal or vertical axis using a left (horizontal) or right (vertical) button press. The location of the middle of the targets (a virtual point for targets composed of even numbers of dots, or the middle of the centre dot for targets composed of odd numbers of dots) was randomised in each trial with the constraint that no dot in a 20-dot target in this location would fall outside the aperture. This constraint was applied irrespective of whether or not the target was composed of 20 dots. An example of a target and noise is shown in Fig. 1.

In each block one target dot number (either 3, 4, 5, 6, 7, 8, 9, 10, 14, 16, or 20 aligned dots) was presented in combination with nine different levels of background dot number (representing nine equal increments of background dot number from some starting value). The range of background dot numbers was chosen to ensure that some (the low background dot numbers) produced accurate detection, whereas others (the high background dot numbers) produced 50% (chance) performance. The order of presentation was pseudo-random, ensuring that in each block each background number was presented 20 times. Following each 150 ms stimulus (target-plus-background) presentation, a mask was presented for an additional 150 ms. The mask was composed of a random configuration of the same target-plus-background dots, and served to ensure that observers could not scrutinise dot afterimages.

Observers received practice at all levels of target dot number until their performance stabilised. Detection thresholds were calculated on the combined results of multiple runs (at least two blocks per condition). Thresholds were reported as the number of background dots giving 75% correct performance, and were calculated from a cumulative normal Gaussian function fit to the data, with its lower asymptote set at 50%, and its upper asymptote set at 100%.

3. Results

3.1. The effects of target dot number

We compared detectability of collinear dots in noise for two strabismic amblyopes using their amblyopic eye versus their non-amblyopic eye. Inspection of Fig. 2 shows that performance in this task improved with dot number and began to saturate with targets of about seven dots. More importantly, for targets of less than seven dots detection was identical for both eyes, whereas for targets of more than seven dots performance was worse with the amblyopic eye (this is evident on either linear [Fig. 2A] or log axes [Fig. 2B]). This result represents inefficiency of the amblyopic eye relative to the non-amblyopic eye in utilising large numbers of target dots.

Using normal observers and short line elements rather than dots, Moulden (1994) reported performance saturation (following an initially rapid stage of improvement) similar to that of the present experiment. Moulden modelled this result as a bilinear function with an inflection point at around seven elements. He interpreted this as the transition from direct summation of stimulus elements within the receptive fields of a single grouping mechanism, to indirect probabilistic summation of stimulus elements due to recruitment of adjacent grouping mechanisms as target element number increases beyond seven. However, this interpretation has been contradicted by the recent finding (Tripathy, Mussap & Barlow, 1996, 1999) that the presence of bilinearity is dependent on the method used to produce targets. If, for example, targets are produced by rearrangement of pre-existing distracter dots proximal to the target location such that local increases in dot density around the target are minimised, bilinearity is reduced and sometimes removed altogether. This occurs due to a flattening of the initial slope of improvement through increased sensitivity to small target-dot numbers. This method has no affect on the slope of the remaining function. On this basis we fit exponential rather than bilinear functions throughout this paper. However, given the nature of the amblyopic effects obtained and the importance of quantifying differences in performance as a function of target dot number (especially for $<$ seven dots relative to $>$ seven dots), bilinear slopes were also fit to the data and resultant statistics (including the location of the inflection point separating the first and second slopes of improvement) provided in table form. For the present experiment, these statistics are summarised in Table 2, and serve to confirm the presence of poorer performance in the amblyopic condition relative to the non-amblyopic condition for targets composed of greater than seven dots.

3.2. The effects of increased positional uncertainty

In the introduction we noted that amblyopic deficits in detection of global targets could be attributed either

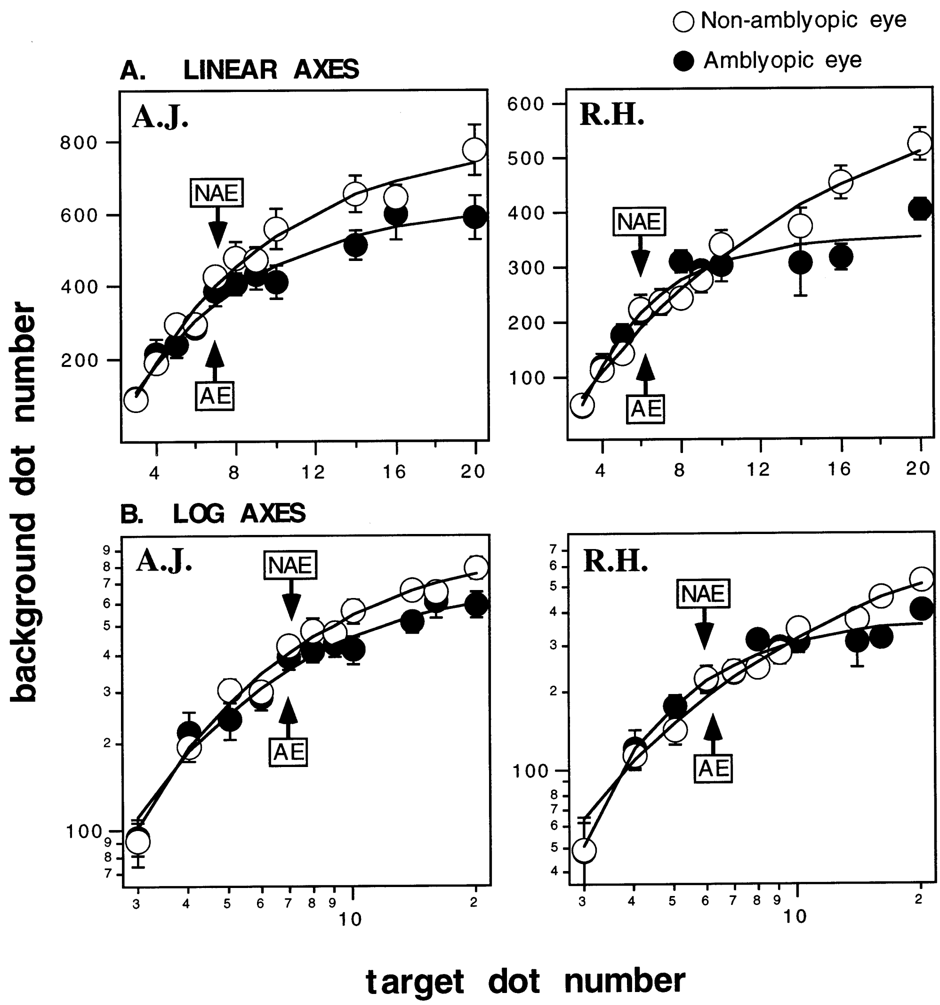

Fig. 2. Target detection performance (at 75%-correct) as a function of target dot number for two observers using their amblyopic versus non-amblyopic eye. NAE- and AE-labelled arrows point to inflection points, as estimated by fitting bilinear functions to the data, for the non-amblyopic and amblyopic functions, respectively. For comparison, ±1 S.E. bars are included.

to abnormal integrative processes or to abnormal cortical units that either: (i) detect dotted lines themselves (a simple cell of V1 could accomplish this since dots were all of the same contrast polarity); or (ii) detect the individual dots making up a line and then feed this information to subsequent integrative processes. The latter position was preferred by Hess, McIlhagga and Field (1997). They reported that matching the positional uncertainty of target elements, simply by jittering the target elements in the non-amblyopic eye to match the estimated intrinsic positional uncertainty of the amblyopic eye, minimised differences in performance. We tested this 'increased uncalibrated jitter' proposition on one amblyope (R.H.) using targets composed of 3, 7, and 20 dots (Hess et al., 1997, did not extend their study to targets composed of greater than eight elements). This was essentially a replication of the results of the first experiment, except that the target dots were jittered orthogonal to their alignment axis according to a normal Gaussian distribution (centred on 0 [no jitter]). Three normal distributions of different standard deviation were sampled from: 0 min (no jitter; identical to Experiment 1), 3.76 and 7.52 min.

Table 2
Summary of bilinear fits for dot-number data

	A.J.		R.H.	
	NAE	AE	NAE	AE
Inflextion point	7.4 (±0.02)	7.1 (±0.02)	6.0 (±0.03)	6.3 (±0.02)
Slope 1	1.40 (±0.01)	1.41 (±0.007)	1.88 (±0.02)	1.81 (±0.02)
Slope 2	0.52 (±0.001)	0.45 (±0.002)	0.75 (±0.001)	0.34 (±0.001)

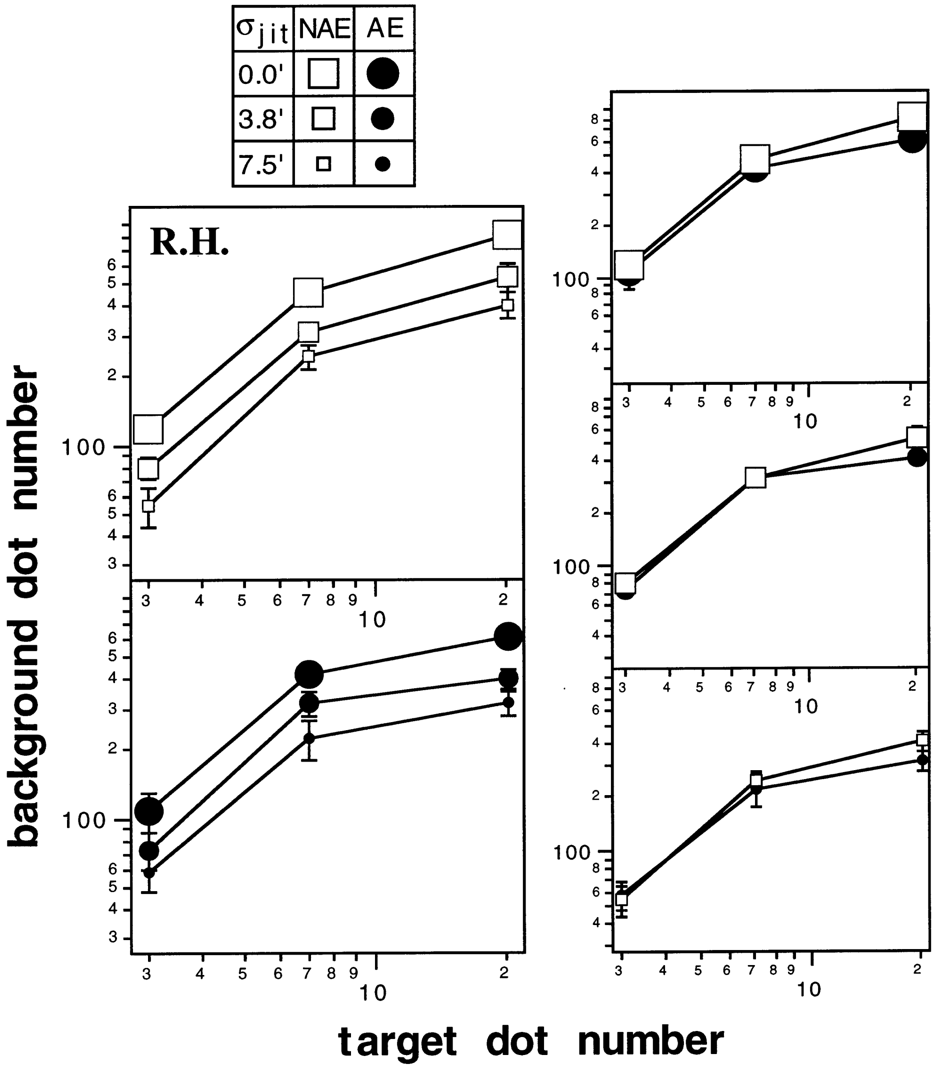

Fig. 3. Target detection performance (at 75%-correct) as a function of target dot number and target dot positional jitter for the amblyopic versus non-amblyopic eye of observer R.H. The two graphs on the left each show the results for the three levels of jitter for each eye separately. The three graphs on the right show the combined results for the amblyopic and non-amblyopic eyes, with each graph representing a different level of positional jitter. For comparison, ± 1 S.E. bars are included.

Table 3
Summary of bilinear fits for dot-jitter data

R.H. (non-amblyopic & amblyopic eye)	0 min jitter		3.8 min jitter		7.5 min jitter	
	NAE	AE	NAE	AE	NAE	AE
Inflextion point	7[a]	7[a]	7[a]	7[a]	7[a]	7[a]
Slope 1	1.60 ($\pm$0.007)	1.61 ($\pm$0.008)	1.60 ($\pm$0.01)	1.74 ($\pm$0.01)	1.76 ($\pm$0.02)	1.57 ($\pm$0.01)
Slope 2	0.54 ($\pm$0.002)	0.36 ($\pm$0.002)	0.51 ($\pm$0.003)	0.23 ($\pm$0.003)	0.49 ($\pm$0.003)	0.34 ($\pm$0.004)

[a] The Corner was fixed at seven for these fits.

As found previously by Tripathy et al. (1996, 1999), jitter reduced dotted-line detection *uniformly* across target dot number. This can be seen from the two leftmost graphs in Fig. 3. These two graphs also show that this uniform reduction in detectability occurred equally for the amblyopic eye as for the non-amblyopic

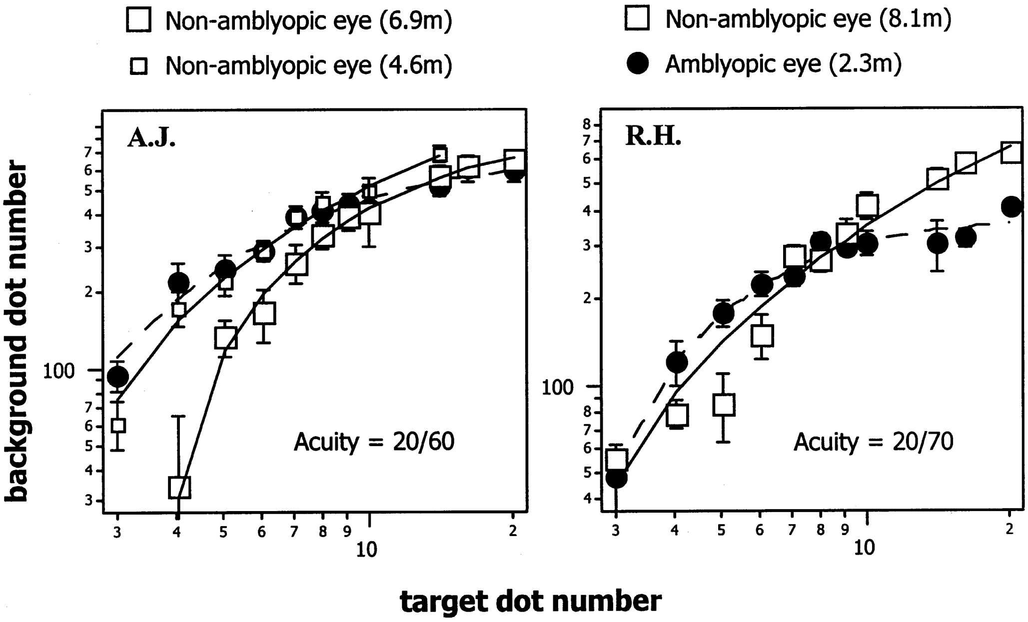

Fig. 4. Target detection performance (at 75%-correct) as a function of target dot number and viewing distance for two observers using their amblyopic versus non-amblyopic eye. The results for the amblyopic eye at 2.3 m (Experiment 1) are also shown. For comparison, ± 1 S.E. bars are included.

eye of R.H.[1] Most importantly, the pattern of results from the first experiment was replicated over all jitter conditions: As shown in Table 3, while the initial slope of improvement was similar (or varied unsystematically) for the two eyes, subsequent improvement was *always* significantly worse for the amblyopic eye. To highlight this, the data from the two eyes were combined in the rightmost graphs of Fig. 3. While the differences appear small when presented on log axes, they were both consistent and large relative to the standard errors. These results are not as predicted according to Hess et al.'s (1997) intrinsic jitter hypothesis, and support instead the proposition that deficits reported in the first experiment actually reflected abnormal integrative processes in amblyopic cortex.

3.3. The effects of visual acuity

Are the differences in performance a consequence of a lowered scale of analysis in the amblyopic visual system? Both observers have reduced visual acuity in their amblyopic eyes (A.J. = 20/60; R.H. = 20/70, corrected). To test the effect of scale, the first experiment was replicated using the non-amblyopic eye at different viewing distances. In addition to the 2.3 m distance employed in the first experiment, A.J. was also tested at 4.6 and 6.9 m (1.5×2.3 m and 3×2.3 m, respectively), and R.H. was tested at 8.1 m (3.5×2.3 m). Increasing the viewing distance for the preferred eye effectively scaled the size, visibility and spacing of the dots to match that of the amblyopic eye. Fig. 4 shows performance in the non-amblyopic eye as a function of viewing distance, with dot detection performance in the amblyopic eye (from the first experiment) included for comparison. The figure shows a minor reduction in target detection performance in the non-amblyopic eye at greater viewing distances. Specifically, performance deteriorated slightly for observer A.J., but only for *small* element numbers (< 10), and did not differ at all for observer R.H. Given that the first experiment revealed detection deficits only with *large* element numbers, it can be concluded that poorer acuity, spatial resolution or reduced dot visibility in the amblyopic condition cannot account for these results.

3.4. The effects dot density/numerosity

As noted in the results of Experiment 1, Tripathy et al. (1996, 1999) demonstrated that dot density differentially affects detectability of dot targets as a function of the number of dots making up the target. They did this by producing targets by rearrangement of pre-existing distracter dots. This method reduced the local increase in dot density resulting when target dots are simply

[1] These data were collected some time after the data from the first experiment. In the intervening period, observer R.H. participated in numerous grouping experiments and a perceptual learning experiment on vernier alignment, the result being a significant improvement in performance in perceptual grouping. (Fortunately, this improvement was equal for the two eyes.) To take this improvement into account, in the present experiment we refer to the 0 min jitter condition as our baseline, rather than referring to the results of the first experiment.

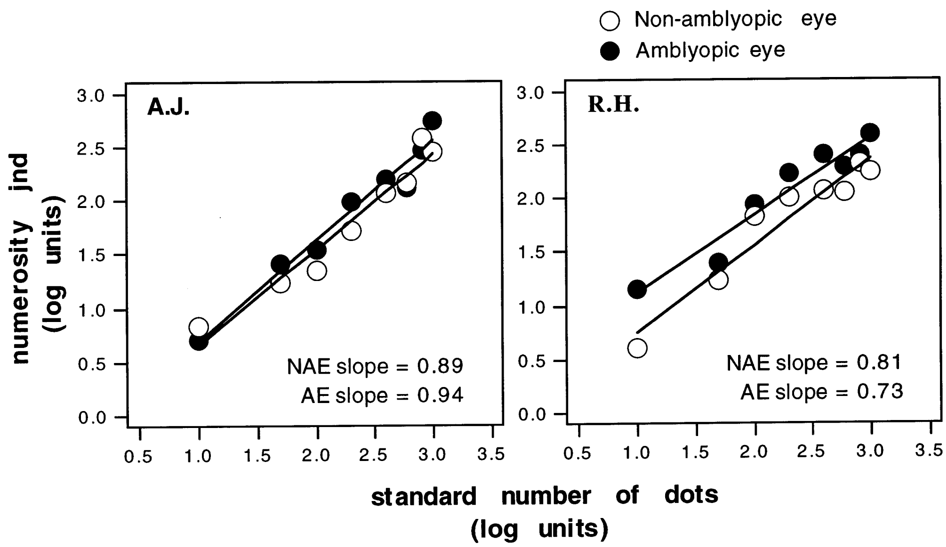

Fig. 5. Numerosity thresholds for two observers using their amblyopic versus non-amblyopic eye, as a function of number of standard dots. For comparison, ±1 S.E. bars are included.

added to distracter dots. The result of this manipulation was an improvement in the detection of target orientation for targets composed of few dots and no change in the detection of target orientation for targets composed of numerous dots (> seven). This is not surprising when one considers that only two distracters in the appropriate lateral-proximal locations are required to make vertical/horizontal discrimination of a vertical three-dot target impossible (i.e. by forming a cross shape).

Since the poorer target detection exhibited by strabismic amblyopes in our first experiment was also dependent on target dot number, it was important to test whether differential sensitivity to dot density accounts for these results. To do so, we would need to show that amblyopes possess relatively greater dot density jnds when large rather than small numbers of dots are involved.

Dot density discrimination performance was compared for the amblyopic versus non-amblyopic eye of the two amblyopes. A 2AFC method of constant stimuli was used to estimate jnds for discriminating differences between the target array of dots relative to some standard. Subjects were told the two arrays differed in the number of dots present, but they could base their discrimination judgements on differences in either dot number or dot density (since stimulus area was kept constant, the two measures are equivalent).

In each block of 180 trials the standard number of dots (s) in the first (standard) display was either 10, 50, 100, 200, 400, 600, 800, or 1000. The second (comparison) display contained $s-3k$, $s-2k$, $s-k$, s, $s+k$, $s+2k$, or $s+3k$ dots, where k is a constant. The two displays were presented for 150 ms each, and separated by a 500 ms ISI. In all other respects methods employed were as described in Section 2.

The results, plotted in Fig. 5, show only slightly superior dot density/numerosity discrimination for the non-amblyopic eye relative to the amblyopic eye, with similar slopes of performance for each condition. These differences were, however, *uniform* as a function of standard dot number/density. In order to account for the results of the first experiment, the amblyopic condition should have resulted in poorer performance only at large standard-dot numbers. However, differences between the two conditions are no greater for large standard dot numbers (high density/numerosity conditions) relative to small standard dot numbers (low density/numerosity conditions).

4. Summary and conclusions

We measured detection of a dotted line in noise with the amblyopic versus non-amblyopic eyes of two strabismic amblyopes and found small but consistent deficits in the amblyopic eye for targets composed of greater than seven dots. Furthermore, we showed that these deficits could not be attributed to interocular differences in spatial resolution, differential sensitivity to dot density, or differential positional uncertainty of underlying processes.

To interpret these results a number of simulations were conducted that measured the accuracy with which various cosine Gabor spatial filters can detect the orientation of collinear dot targets (from three to 18 dots in extent), as a function of the number of random distractor dots (for details refer to Appendix A). The question addressed was whether the amblyopic deficits reflect deficiencies in integrative processes involved in perceptual grouping (cf. association models), or whether the locus of the deficit is in simple spatial filters involved in coding for spatial-frequency and orientation (cf. spatial-frequency models). The critical difference between these interpretations is that putative integrative processes combine selectivity for overall target length with fixed selectivity for target width. Their global receptive fields are thus elongated and narrow. On the other hand, simple spatial filters are scaled versions of a single receptive field, scaled to match either target length (in which case their spatial-frequency is inversely proportional to target dot number) or target width (in which case their spatial-frequency does not change as target dot number increases).

To test these alternatives we measured the sensitivity of each filter in terms of the number of distractor dots giving 75%-correct identification of the orientation (vertical versus horizontal) of target dots as a function of target dot number (i.e. we used the same procedure as in the psychophysical experiments reported above). The filter types were: (i) integrative filter in which filter length is scaled to overall target length and filter width is fixed to a constant target width (specifically, the fundamental frequency of the dot chain); (ii) length-scaled spatial filter in which both filter length and width are scaled to overall target length; (iii) width-scaled spatial filter in which both filter length and width are fixed to a constant target width. Note, that in each case we were concerned only with the dimensions of the filter as predicted by different models of dotted line detection, and not with the neural connections thought to produce these filter dimensions.

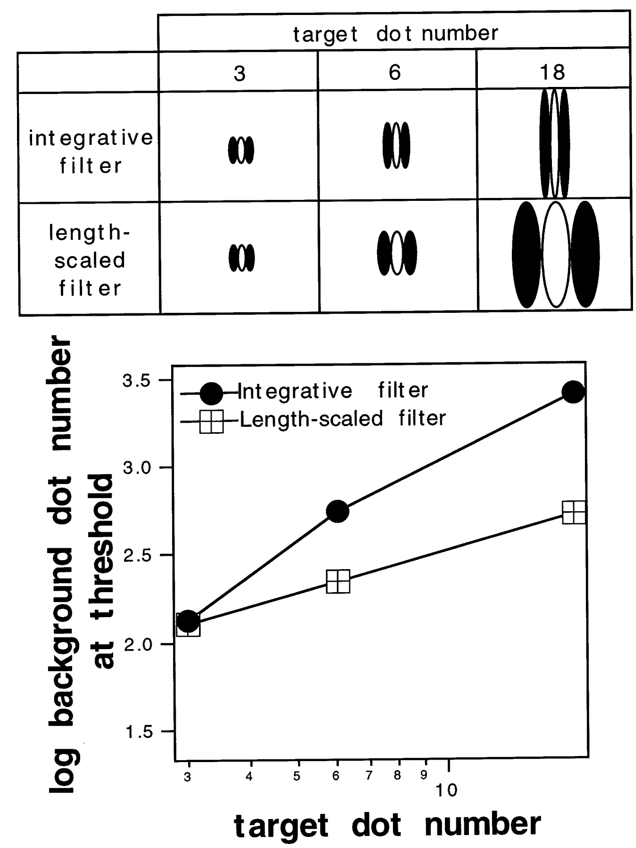

Fig. 6. Results of simulations (I). Log threshold number of distractor dots (giving 75%-correct detection), as a function of target dot number, for integrative filters and length-scaled filters.

Since the amblyopic deficits revealed in the present experiments were limited to large target dot numbers, the filter that is most critical for detecting large targets is the most likely candidate for explaining these deficits. Inspection of Fig. 6 shows that while both the integrative and length-scaled filters were equally sensitive to small target dot numbers, the integrative filter was far superior at large target dot numbers. The length-scaled filter failed to perform as well because its decreasing spatial-frequency with increasing target dot number resulted in a progressively greater proportion of false alarms being made. The superior performance of the integrative filter supports the proposition that the amblyopic deficits in detecting large numbers of target dots reflect abnormal processes of perceptual grouping. (Note, as with previous attempts at modelling perceptual grouping [e.g. Tripathy et al., 1999] we were not able to replicate the bilinear slope of improvement reported by Moulden, 1994, with any of the filters).

Fig. 6 does not show the results of the width-scaled filter. The ability of this filter to detect dot targets (of greater than one dot in length) depended on the spatial-frequency chosen for the filter. When its spatial-frequency was equal to the fundamental frequency of the dot chain (cf. the integrative filter) it was incapable of reliably detecting collinear arrangements of these dots. Filters scaled to a lower-frequency could detect targets, but their fixed spatial-frequency tuning resulted in severe response saturation once target length exceeded filter length.

A second issue explored was the nature of the neural deficit in our amblyopic observers. Two types of deficit at the level of subunits that feed into integrative processes were simulated by degrading the target dots: *Undersampling* was simulated by removal of 1/3 of the target dots; *positional uncertainty* was simulated by randomly jittering the x/y position of 1/3 of target dots by -1, or $+1$ dot widths. The results, plotted in Fig. 7, show that both forms of stimulus degradation reduced sensitivity of the integrative filter uniformly as a function of target dot number. This is in line with most psychophysical results (e.g. Hess et al., 1997; Tripathy et al., 1999), and make it unlikely that either undersampling or positional uncertainty are responsible for the abnormal integration (at large target dot numbers) evident in our experiments.

However, we considered the possibility that abnormal subunit inputs could lead to the development of integrative processes that are *stunted*. This might result from disruption of the normal development of connections between first-stage subunits and second-stage integrators, or between units of like response preference via long-range horizontal connections (cf. Polat et al., 1997). We simulated this scenario using integrative filters that

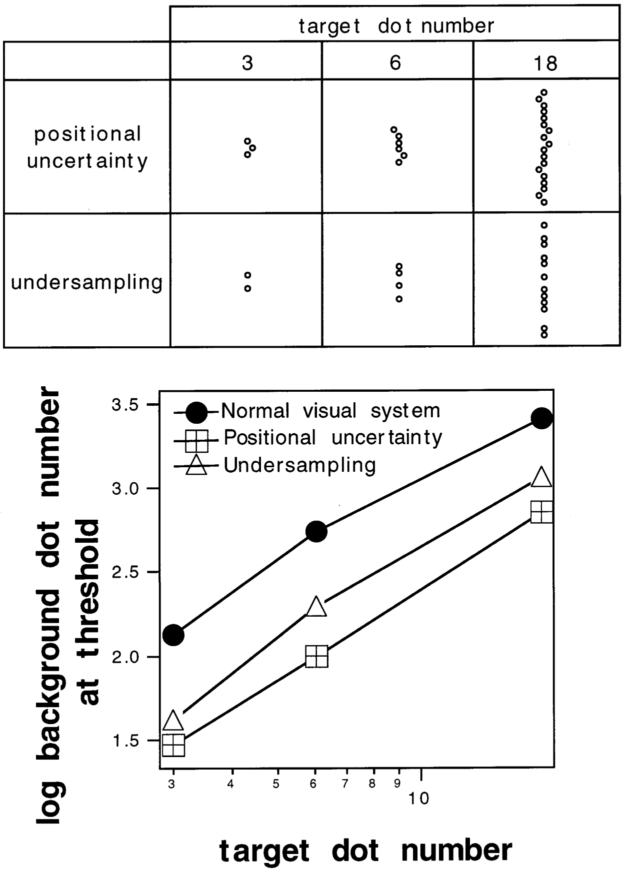

Fig. 7. Results of simulations (II). Log threshold number of distractor dots (giving 75%-correct detection), as a function of target dot number, for three versions of integrator subunits: Normal, positionally uncertain, and undersampled.

do not increase in length in proportion to target length due to disproportionately greater numbers of short versus long filters (an exponent of 0.4 was used; see Appendix A). The results in Fig. 8 show that stunted integrative filters would indeed result in an impaired ability to detect long chains of target dots. An alternative possibility was also considered: that integrative processes in amblyopic cortex are set at a lower base spatial-frequency (cf. Levi, 1988). This was tested by decreasing the spatial-frequency of the integrative filters by a factor of 3. The results of this manipulation are included in Fig. 8 and show that, unlike our amblyopic data, a uniform drop in sensitivity results.Recently, Hess et al. (1997) reported evidence that amblyopic grouping deficits could be accounted for by positional uncertainty at the level of first-stage units (at least for targets of less than eight elements). However, our data in conjunction with the simulations show that this argument does not apply when the number of elements is large such that: (i) detection thresholds are limited by grouping processes rather than by processes involved in element detection; and (ii) there is a discrepancy between target length and the length of the largest spatial filters that are reasonably sensitive to both target element width and overall target length.

Some aspects of our psychophysical results are consistent with the results of a recent study showing reduced sampling efficiency when the number of elements is large. Wang, Levi and Klein (1998), using an ideal observer model, showed that the visual system of strabismic amblyopes is characterised by both positional uncertainty and markedly reduced sampling efficiency. More recent studies show that while the normal human fovea is very efficient in using highly visible Gabor samples to determine the orientation of an E-like pattern, at high spatial frequencies strabismic amblyopes are much less efficient (Levi, Klein & Sharma, 1999).

In conclusion, the results of the present experiments interpreted in light of the simulations performed indicate that the amblyopic deficits in detecting targets composed of large numbers of dots reflect abnormalities at the level of integrative processes rather than at the level of subunits that feed into these processes.

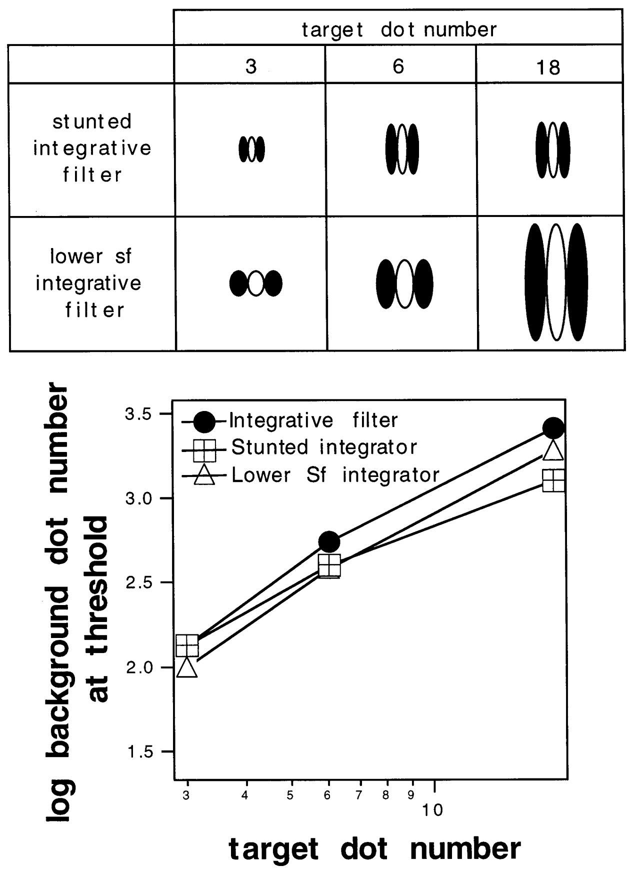

Fig. 8. Results of simulations (III). Log threshold number of distractor dots (giving 75%-correct detection), as a function of target dot number, for three versions of integrative filters: Normal, stunted (exponent = 0.4), and low spatial-frequency (a factor of three lower than normal).

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Appendix A

Simulations were conducted in Matlab™ according to the following method:

1. In each trial the centre of a 74 × 74 pixel array was filled with 3, 6, or 18 collinear target dots of 1 pixel diameter (separated vertically by 1 pixel), and a number (between 1 and 3500) of randomly-placed distractor dots.
2. The stimulus array was convolved with various linear Gabor filters of the general form:

$$G(x, y) = \cos(2\pi f x_c) \exp\left(-\left(\frac{y_e^2}{\sigma_y^2} - \frac{x_e^2}{\sigma_x^2}\right)\right)$$

   where $x_c = x\cos(\theta_c) + y\sin(\theta_c)$, $x_e = x\cos(\theta_e) + y\sin(\theta_e)$, $y_e = y\cos(\theta_e) - x\sin(\theta_e)$, with f usually set to $(2d)^{-1}$ (where d *is* dot diameter, i.e. the fundamental frequency of the target dot chain), and set first to vertical and then to horizontal.
3. Three types of these vertical Gabor filters were produced by manipulating their spatial dimensions:
   3.1. integrative filter: $f = (2d)^{-1}$, $\sigma_x = d$, $\sigma_y = dn$;
   3.2. length-scaled filter: $f = (2dn)^{-1}$, $\sigma_x = dn$, $\sigma_y = dn$;
   3.3. Width-scaled filter: $f = (2d)^{-1}$, $\sigma_x = d$, $\sigma_y = d$. (where n is the number of target dots).
4. The maxima of the vertical and horizontal filter outputs for each filter type were found. If the vertical maximum was greater than the horizontal maximum a correct response was recorded (because target arrays were always vertically collinear).
5. Each combination of target dot number and distractor dot number was presented at least 60 times, and 75%-correct performance was estimated as for the psychophysical data of the previous experiments.
6. Four degraded visual systems were also simulated in the context of the integrative filter:
   6.1. Undersampled subunits: removal of a random 1/3 of target dots;
   6.2. Positionally uncertain subunits: 1/3 target dots jittered by d;
   6.3. Stunted integrative filter: $f = (2d)^{-1}$, $\sigma_x = d$, $\sigma_y = 3d(n/3)^{0.4}$;
   6.4. (4) Low sf integrative filter: $f = (6d)^{-1}$, $\sigma_x = 6d$, $\sigma_y = dn$.

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